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A COMPRESSED HYDROGEN GAS STORAGE SYSTEM WITH AN INTEGRATED PHASE CHANGE MATERIAL

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Abstract—A dynamic fueling model is built to simulate the fueling process of a hydrogen tank with an integrated passive cooling system. The study investigates the possibility of absorbing a part of the heat of compression in the high latent-heat material during melting, with the aim of keeping the walls below the critical temperature of 85 °C, while filling the hydrogen at ambient temperature. Results show that a 10-mm-thick layer of paraffin wax can absorb enough heat to reduce the adiabatic temperature by 20 K when compared to a standard Type IV tank. The heat transfer from the gas to the phase change material, mainly occurs after the fueling is completed, resulting in a higher hydrogen peak temperature inside the tank and a lower fuelled mass than a gas-cooled system. Such a mass reduction accounts for 12% with respect to the case of a standard tank system fuelled at -40 °C.

Keywords: phase change material, hydrogen storage, hydrogen fueling, dynamic model, heat transfer.

INTRODUCTION

Phase change materials (PCMs) have been widely studied as thermal energy storage options for a variety of applications, ranging from solar heat storage to cooling/heating systems for buildings [1]–[6]. A significant less explored field of application is hydrogen storage. Very few studies investigated the possibility of integrating PCMs to absorb the heat that generates during hydrogen fueling into the tank, and most of them are limited to hydrogen storage in metal hydrides for stationary applications [7].

In this preliminary study, the advantages and drawbacks that arise from applying such a technology to compressed gaseous hydrogen (CHG) systems are addressed with respect to light duty vehicles. The tank design and operation must ensure the mechanical stability during fueling, by preventing the walls to reach the critical temperature of 85 °C after hydrogen expansion.

This is typically done, in practice, by cooling the hydrogen gas to -40 °C before filling into the tank. At this condition, the adiabatic gas temperature at the end of the refueling process is below 85 °C, ensuring the system's mechanical stability, even in presence of hot spots at the walls. However, such systems are costly due to non-conventional cooling systems.

The use of a passive cooling system inside the tank is here investigated with the final goal to reduce the cooling demand at the refueling station by absorbing a significant amount of the heat of compression inside the tank during fueling and, at the same time, keeping the walls below the critical temperature.

METHODS

At first, a computational model that enables to calculate the PCM temperature and provides information on the position of the moving melting layer is developed by means of the effective capacity method [8]. Then, such a model is applied to a 10-mm-thick layer on the inner wall of a storage tank, which is filled with high pressure hydrogen gas. The tank is inserted in a refueling system, where the tank type

(e.g. Type III, Type IV) and the ambient temperature constitute the main inputs that are passed to the model component that selects the appropriate refueling protocol to be used (see Ref. [9]). The fueling pressure (350 or 700 bar) and the charging pressure ramp are completely defined by the refueling protocol.

During hydrogen fueling into the tank, the gas temperature increases and a part of this heat is transferred to the PCM layer and through it to the liner and carbon fiber that constitute the tank walls. In the tank thermal model, the energy balances and heat transfer equations are solved for the wall, which has been discretized by means of the finite volume method in Dymola® environment [10]. The thermodynamic and heat transfer models employed for the tank are described in detail in Ref. [11]. The main outputs include the gas temperature, the temperature profile in the PCM layer and in the walls at different locations, as well as the stored hydrogen mass. A simplified sketch representing the dynamic fueling model is presented in Fig. 1.

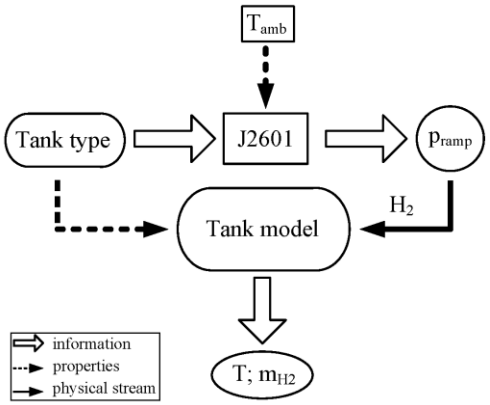


Figure 1. Flux diagram of the fueling model.

In Fig. 2 the dimensions of the Type IV tank considered in this study are reported, while the liner and carbon fiber properties are given in Ref. [12]. The inner volume is approximately 126 L, which is a realistic size for a practical storage system to be used in a fuel cell vehicle (FCV).

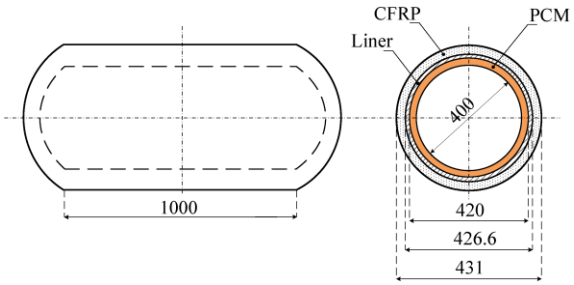


Figure 2. Type IV tank longitudinal and transversal sections. All dimensions are in mm.

The PCM used is a paraffin wax with a melting temperature of 55 °C, latent heat of 224.36 kJ/kg and thermal conductivity that varies between 0.24 $W \cdot m^{-1} \cdot K^{-1}$ for the solid and 0.18 $W \cdot m^{-1} \cdot K^{-1}$ for the liquid phase. More details on the PCM properties can be found in Ref. [8]. In practice, a thin aluminum layer can be used to keep the phase change material in place and prevent it to flow to the bottom of the tank during melting.

In Table 1, an immediate comparison between the overall size and weight of the two tanks is given. The two tanks are compared with respect to the same inner volume.

Table 1. Type IV tank and novel design: size and weight.

Case	V_{tot} [L]	m_{tank} [kg]	m_{PCM} [kg]
Standard Type IV	160	45.6	/
Type IV with PCM	174 (+9%)	57.75 (+27%)	10

When a 10-mm-thick layer is inserted on the inner wall, then the overall tank volume increases by 9%, and it's mass by 27%. Such a mass increase is mainly due to the PCM, which accounts for 10 kg of the extra 12 kg added to the tank. The rest is due to the larger masses of the liner and carbon fiber reinforced polymer (CFRP) that result from keeping the same thickness at larger radii. At the end, while the difference in volume is modest, the mass increase appears quite significant. However, the extra weight added to the system is relatively negligible when the comparison is made with respect to the overall FCV mass.

RESULTS

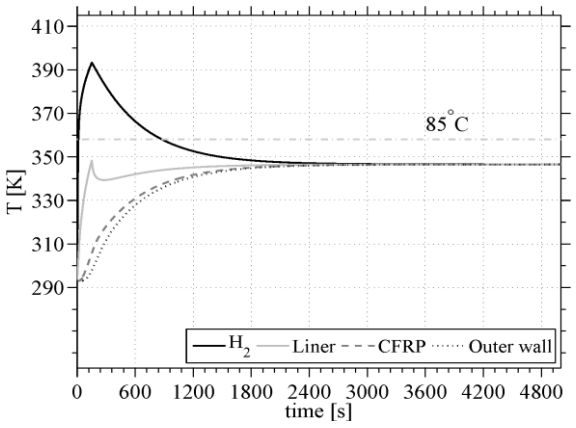
A comparison in results between a standard Type IV tank and the design with integrated PCM is here provided. The temperatures in the plots refer to the location corresponding to half of the thickness of each wall layer.

In Fig. 3 the results obtained under the assumptions of adiabatic outer wall and absence of hydrogen cooling at the refueling station are shown. The gas is filled at the ambient temperature of 20 °C, which is the initial equilibrium temperature for the walls before the fueling takes place, and rapidly heats up due to the compression into the tank. With a pressure ramp of 282 bar/min, the fueling is completed in approximately 150 s, and the gas reaches its peak temperature around 390 K. Being the outer tank wall adiabatic, the heat can only be transferred from the gas to the surrounding walls and the system tends to thermal equilibrium.

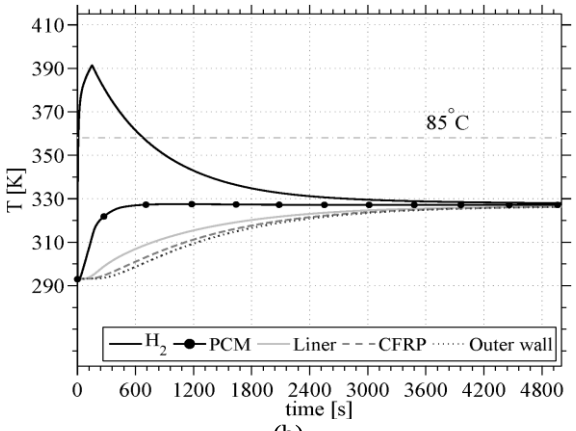
In Fig. 3a, where the results for a standard Type IV tank are presented, the adiabatic temperature is around 74 °C and the thermal equilibrium is reached at 3300 s. During fueling, the gas thermal convection coefficient is set to 150 $W \cdot m^{-2} \cdot K^{-1}$ (see Ref. [12]) and the plastic liner experiences higher heat rates, whereas, when the filling process is completed, the convection coefficient drops to 50 $W \cdot m^{-2} \cdot K^{-1}$ and the liner undergoes an abrupt decrease in temperature, because more heat is transferred outward to the wall, and then it heats up again.

Under these conditions, the adiabatic temperature is below the critical value for both the liner and CFRP. However, the presence of hot spots where the local temperature might be greater than 85 °C should not be excluded, with the result that the mechanical stability of the tank might be damaged. In Fig. 3b the temperature results that refer to the novel Type IV tank are presented.

The system reaches the thermal equilibrium at a temperature around 53 °C, which is approximately 20 °C lower than for the standard tank case. It follows that, the phase change material succeeds in absorbing a significant amount of the heat of compression, keeping the walls considerably below the critical temperature at any time. However, as in the previous case, the hydrogen temperature seems affected by the heat transfer to the walls only after the filling process is completed and large times are required to reduce the gas temperature below 85 °C and later reach the thermal equilibrium.



(a)



(b)

Figure 3. Temperature profiles for a standard Type IV tank (a) and for a Type IV tank with integrated PCM at the inner wall (b). No hydrogen cooling at the station.

By comparing Fig. 3b with Fig. 3a, it can be observed that the peak temperature is reduced by only 2 K when the phase change material is inserted, meaning that the heat transfer rates are not high enough to effectively exchange the heat of compression during fueling. Indeed, the high thermal resistances at the hydrogen/gas interface, as well as the poor thermal properties of the paraffin wax, limit the gas cooling and slow down the heat transfer process.

At the end, two main conclusions can be drawn. First, the presence of hot spots at the walls cannot be entirely excluded, although the insertion of the PCM layer makes such a situation quite unlikely; second, the gas density during fueling is the same for the two tanks, resulting in the same overall mass that is fuelled into the storage system. With respect to the latter assertion and even if it is assumed that no hot spots would result in practice, the present novel design cannot provide the same storage performances of a regular CHG system, where the hydrogen is cooled prior to filling.

This can be observed in Fig. 4 where the hydrogen mass inside the tank is presented at different gas inlet temperatures. At time zero, the inside of the tank is at the initial conditions of 20 bar and 20 °C and the resulting initial hydrogen mass is 0.2 kg. When refueling starts, the gas mass increases, until the target charging pressure is reached at 150 s. Then, the inlet valve closes and the stored mass remains constant. For the same storage volume, the overall fuelled mass is reduced from 4.67 kg, when hydrogen is filled at -40 °C, to 4.17 kg in absence of gas cooling. This corresponds to a decrease by 12% in the storage capacity of the system.

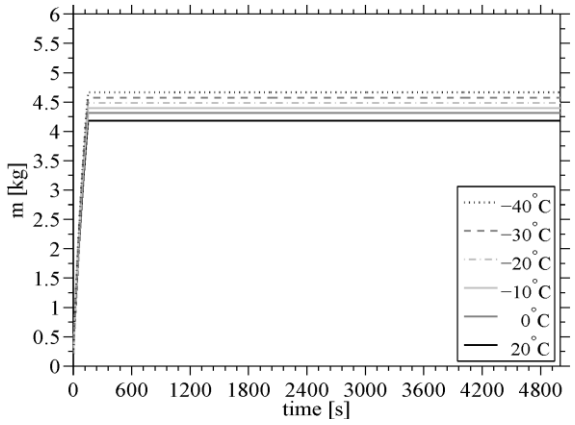


Figure 4. Hydrogen mass fuelled into the tank for different inlet temperatures.

Ideally, the novel tank design should guarantee the mechanical stability even in absence of gas cooling and store the same amount of hydrogen as a regular gas-cooled system. If this could be realized, the only drawbacks would be the larger weight and volume, whereas the benefits would include the energy saving and the heat exchanger size-reduction/removal at the refueling station, as well as the increase in the filling process reliability. In order to achieve such benefits, the heat transfer from the gas to the phase

change material must be enhanced and, at the same time, the PCM physical properties should be carefully tailored.

As the hydrogen convection coefficient is determined by the refueling conditions and the resulting turbulence inside the tank, one should mainly focus on the heat transfer area augmentation and the thermal conductivity enhancement for the phase change material. For the former, solutions include extended surfaces and PCM encapsulation in the liner lattice [13]. For the second, different strategies can be employed, as the use of a PCM with favorable thermal properties or enhancing the heat transfer by forming PCM stable composites with a highly conductive material, as well as inserting the PCM in a metallic structure (e.g. aluminum foams) [14, 15].

CONCLUSIONS

Two tank designs are considered in absence of hydrogen-cooling at the refueling station: a standard Type IV tank and a novel tank design that includes a 10-mm-thick layer of PCM at the inner volume. Results show that the integration of the PCM reduces the system's adiabatic temperature from 74 °C to 53 °C when compared to the standard case. Also, the liner and carbon fiber temperatures are maintained below the critical limit of 85 °C at any time. However, due to the modest heat transfer rates at the gas/PCM interface and in the PCM thickness, the hydrogen peak temperature is essentially independent from the PCM insertion. This results in a higher gas temperature inside the tank during fueling, and a lower density (thus mass) of the stored hydrogen. Future research should focus on different strategies for heat transfer improvement, including surface augmentation and PCM thermal properties enhancement.

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